Prototyping the Proximity-Focusing Aerogel Ring-Imaging Cherenkov Detector for the Future Electron-Ion Collider

Jose Gregorio Esparza III[1], Dr. Wenliang Li[2], Dr. Abhay Deshpande[2]

[1] Columbia University, Department of Physics

[2] Stony Brook University, Center for Frontiers in Nuclear Science

Background

The Electron-Ion Collider (EIC) is a particle accelerator currently under construction at Brookhaven National Laboratory designed to collide spin-polarized beams of electrons (e) with beams of protons (p) or heavy nuclei (A). Its primary goal is to address outstanding questions in nuclear structure concerning the origin of mass and spin in nucleons (i.e., protons and neutrons), the spatial distribution of quarks and gluons inside nucleons, and the nature of a QCD state of matter called a color glass condensate.

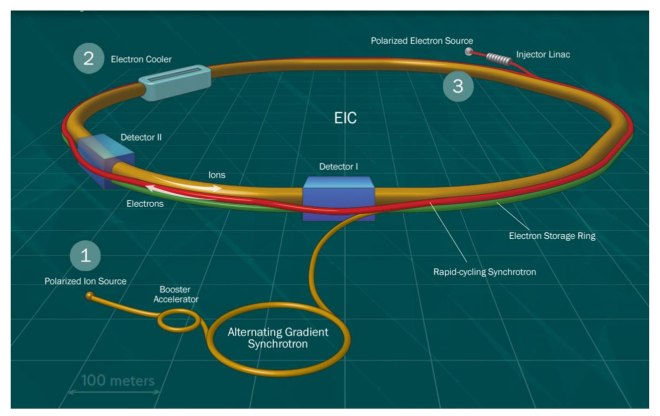


Figure 1: Schematic of EIC Complex

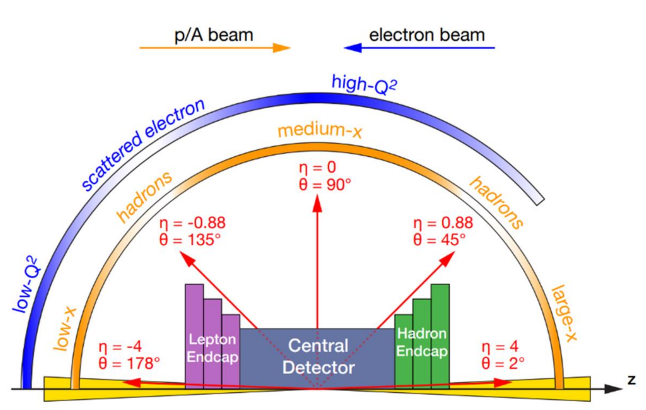


Figure 2: Schematic of EIC Detector Hemispheres

In order to achieve these goals, it is necessary to construct a particle identification device (PID) with the ability to identify scattered electrons and hadronic final states in the pseudorapidity range $-3.5 \leq \eta \leq -1.5$ (i.e., the backward region) for studies of e+p and e+A collisions. At Interaction Point 6 of the EIC, the site of the planned Electron-Proton/Ion Collider (ePIC) detector, a proximity-focusing Aerogel Ring-Imaging Cherenkov (pfRICH) detector has been proposed to fulfill these PID requirements.

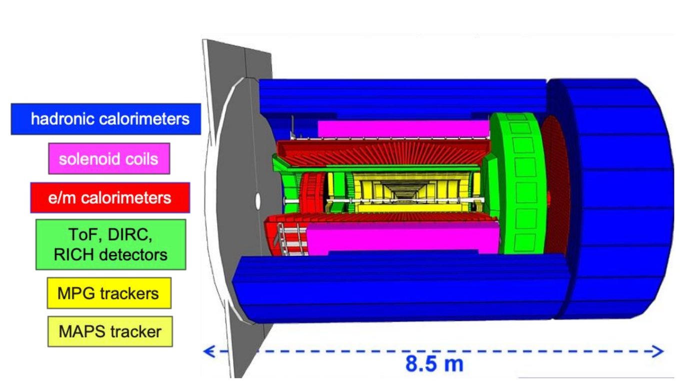


Figure 3: Schematic of ePIC Detector

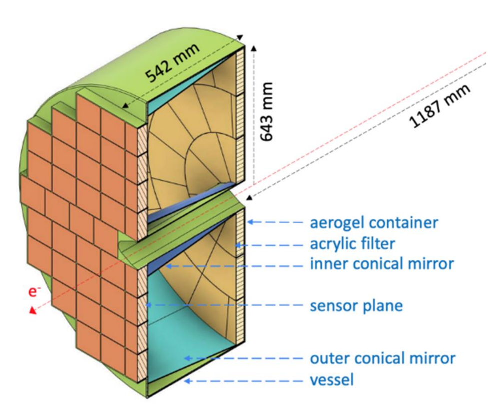


Figure 4: Schematic of pfRICH Detector for PID in the ePIC Detector

Detector Visualization

The pfRICH geometry is defined using the DD4hep description toolkit in the EIC shell software environment. By modifying the specific GDML file that corresponds to the pfRICH geometry only, we can reduce the geometry content of the pfRICH detector to only include components of interest for isolated study. For our studies, we selected a single quadrant of the geometry and retained the following components: the aerogel plane with radiator tiles and corresponding spacers, the inner and outer conical mirrors, and the photosensor plane complete with high-rate picosecond photodetectors (HRPPDs) and their corresponding spacers.

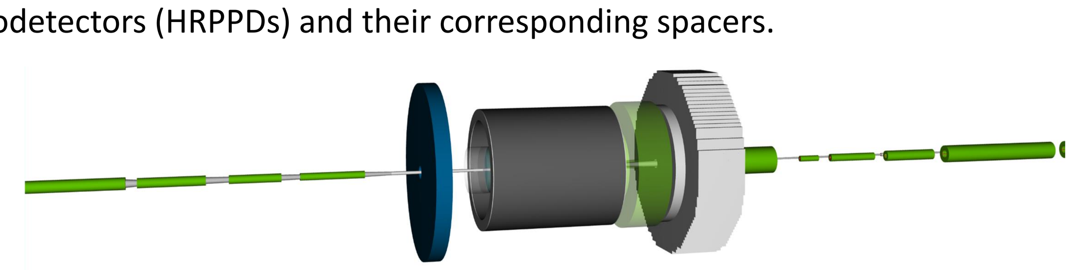


Figure 5: Cutaway of the ePIC Detector as it is defined in DD4hep

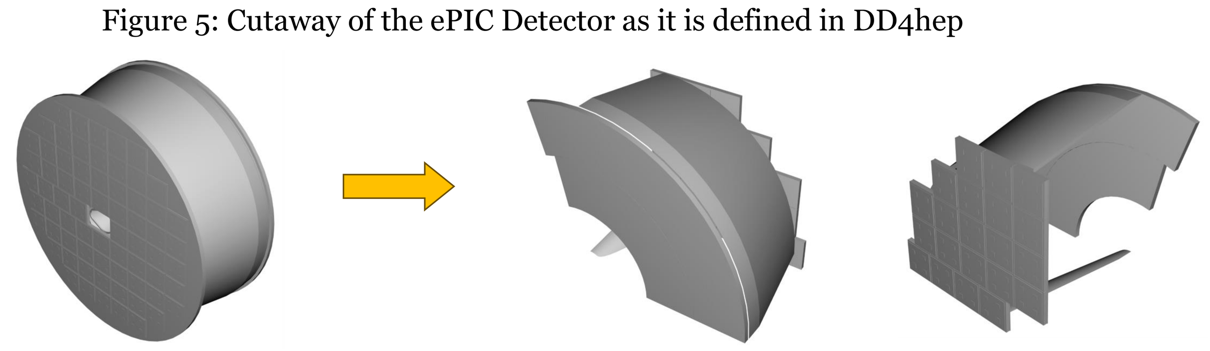


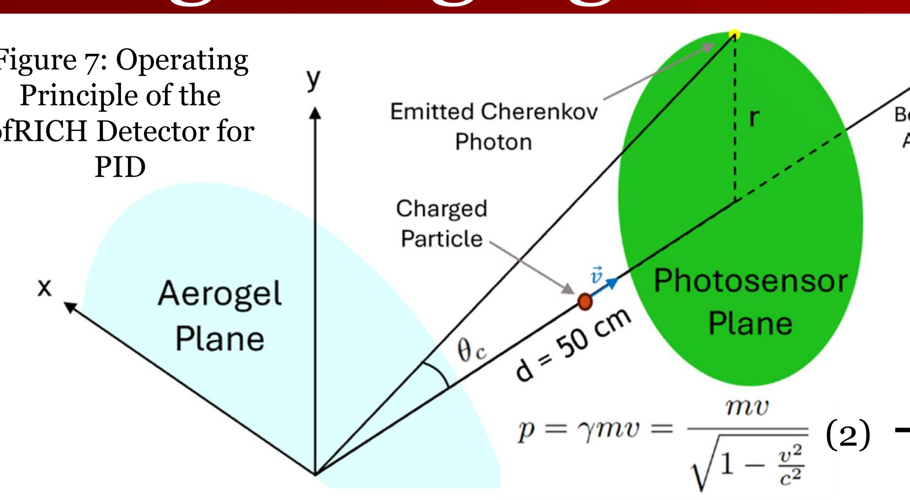
Figure 6: (a) pfRICH Detector in DD4hep (b) Front View of Single-Quadrant pfRICH Detector (c) Back View of Single-Quadrant pfRICH Detector

Abstract

The current design for the proposed pfRICH detector relies on the analysis of Cherenkov radiation produced during the accelerated charged particles' traversal through aerogel material with a known index of refraction. Using the Geant4 software toolkits and npsim steering files for detector simulations, we study the predicted Cherenkov photon coverage on the pfRICH's photosensor plane using single-particle simulations on a single quadrant of the detector's geometry for each of three particles: the pion (π^+), the proton (p^+), and the kaon (K^+). We generate plots for the theoretically computed Cherenkov angles and rings for each particle for a given momentum range for comparison with future experimental studies of actual photosensor hits. To complement these efforts on the hardware side, we also constructed a physical mock-up of a single quadrant of the pfRICH detector. The physical mock-up will be used in conjunction with the data retrieved from our simulations to inform potential modifications of the actual pfRICH detector and is used here to determine the viability of certain materials for use in future prototyping of the pfRICH detector.

Ring-Imaging Detection Technique

Figure 7: Operating Principle of the pfRICH Detector for PID



θ_c = angle of emission of Cherenkov radiation
c = speed of light in vacuum
n = refractive index of radiator = 1.045
v = velocity of charged particle
p = relativistic momentum of particle
d = distance between aerogel and photosensor planes

$$\cos\theta_c = \frac{c}{nv} \quad (1)$$

$$p = \gamma m v = \frac{mv}{\sqrt{1-\frac{v^2}{c^2}}} \quad (2) \longrightarrow v = \frac{p}{\sqrt{m^2 + \frac{p^2}{c^2}}}$$

Cherenkov Angle (in c = 1 units): $$\theta_c = \cos^{-1}\frac{\sqrt{m^2+p^2}}{np} \quad (3)$$

Radius of Cherenkov Ring: $$r = d\tan\theta_c \quad (4)$$

The angle of emission of Cherenkov radiation due to the charged particle's traversal through the aerogel is related to the particle's velocity by equation (1). This equation can be written in terms of the particle's relativistic momentum (2) and rest mass and solved for the Cherenkov angle to give equation (3). The Cherenkov angle is then connected to the observed Cherenkov photon coverage on the photosensor plane by relating it to the emitted photon's final axial position from the z axis, yielding equation (4). Since the refractive index of the aerogel is known and the momentum of the particle can be determined using a tracking system, the Cherenkov emission angle can be used to determine particle mass, which is used to identify the particle that traversed the aerogel at a certain time.

Detector Studies of Cherenkov Photons

The particle gun in the steering files used to run the single-particle simulations was configured to deliver 1500 particles of a particular type with momenta 1-10 GeV/c into the pfRICH detector. The following angular ranges of randomly distributed directions for Cherenkov photon physics were selected: $154° \leq \theta \leq 177°$ (corresponding roughly to the pseudorapidities $-3.5 \leq \eta \leq -1.5$, according to the equation $\theta = 2\tan^{-1}(e^{-\eta})$) and $0° \leq \phi \leq 360°$. The proximity gap separating the aerogel and photosensor planes was set to d = 50 cm. The simulations were run using npsim and Geant4, and the output data were analyzed using ROOT, an open-source data analysis software framework.

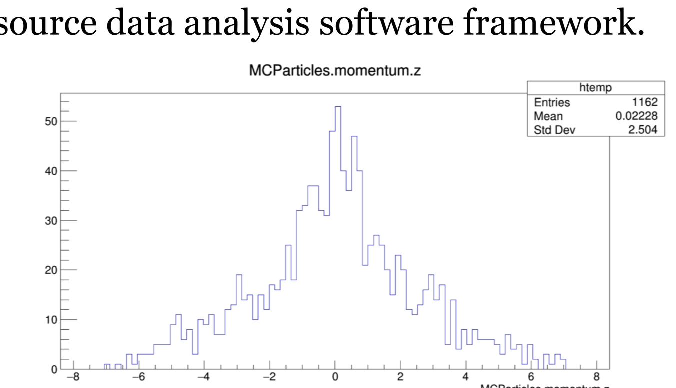


Figure 8: Particle Momentum Histogram (the π^+ case is shown here)

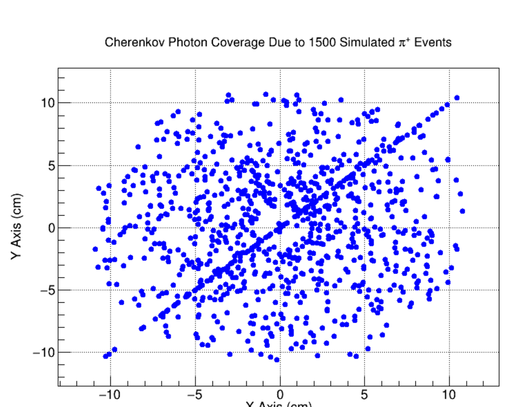


Figure 9: Cherenkov Photon Coverage of 1500 Simulated π^+ Single-Particle Events

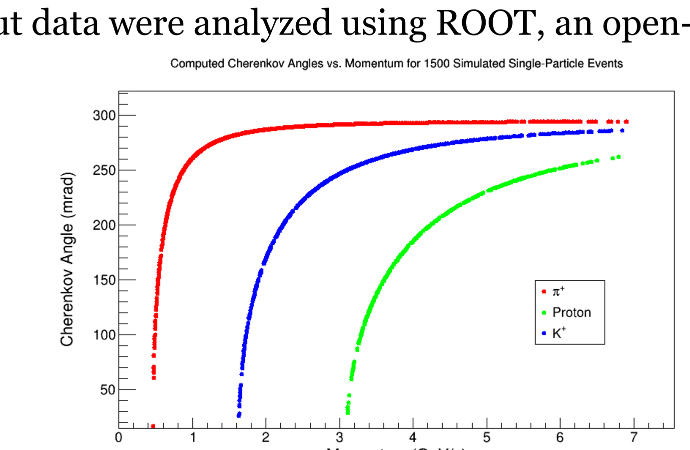


Figure 10: Computed Cherenkov Angle vs. Momentum Graph for All Three Particles

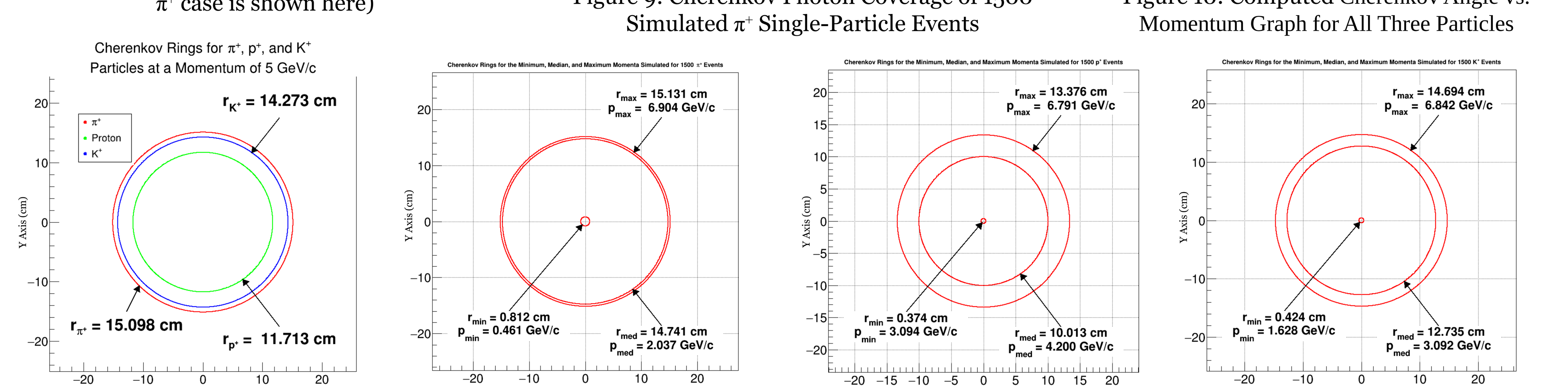


Figure 11: (a) Computed Cherenkov Rings for all Three Particles at a Momentum of 5 GeV/c (b) Cherenkov Rings for Recorded Photon Hits for 1500 Simulated π^+ Events (c) Cherenkov Rings for Recorded Photon Hits for 1500 Simulated p^+ Events (d) Cherenkov Rings for Recorded Photon Hits for 1500 Simulated K^+ Events

Physical Realization

The constructed mock-up for the pfRICH prototype is a physical realization of the geometry shown in Figures 6b and 6c. In order to anchor the aerogel plane, the inner and outer mirrors, and the photosensor plane components, these components were glued onto three additional walls (two rectangular, one circular) using epoxy adhesive. The rectangular walls were constructed by pasting two sheets of carbon fiber onto opposite sides of a Plascore honeycomb panel. The quarter-circle wall was similarly constructed by pasting two sheets of plastic onto opposite sides of a Plascore honeycomb panel and then rolling the resultant straight wall on a large mandrel to give it its curved shape. 3D-printed endcaps made of polylactic acid (PLA) were used to hold the plastic aerogel and HRPPD prototype components in place. Sheets of aluminum were used for the mirrors.

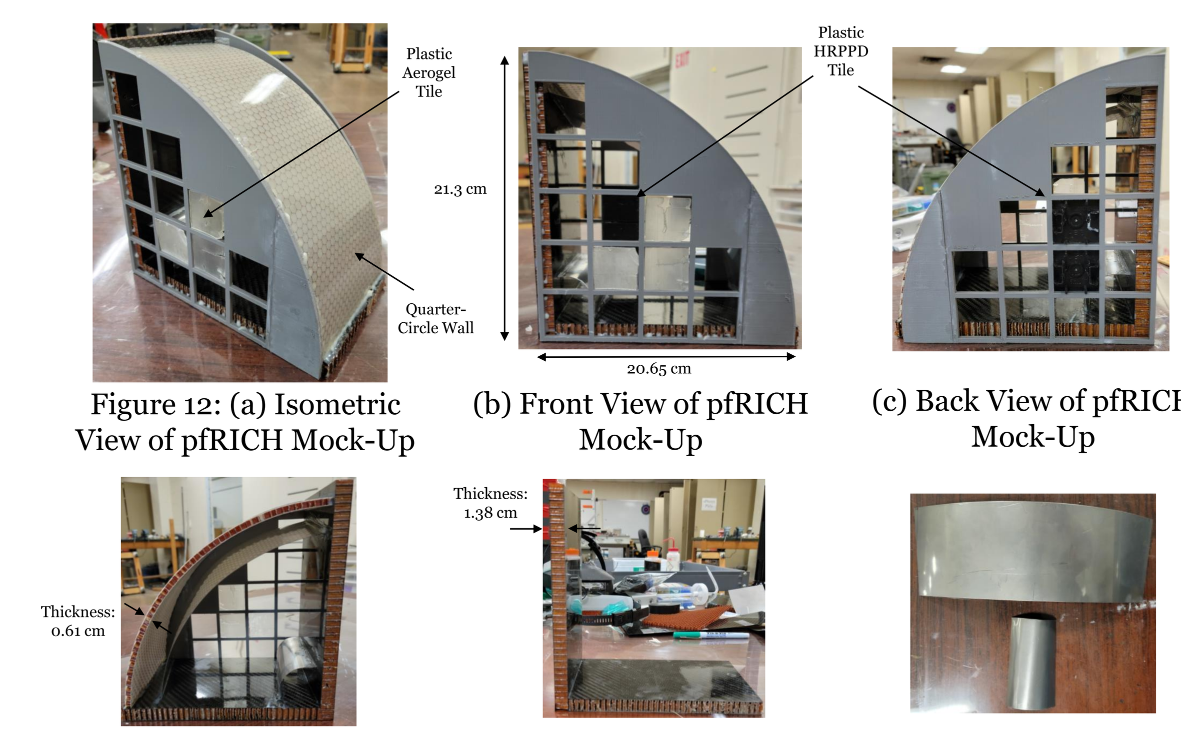


Figure 12: (a) Isometric View of pfRICH Mock-Up (b) Front View of pfRICH Mock-Up (c) Back View of pfRICH Mock-Up (d) Back (Interior) View of pfRICH Mock-Up (e) Close-Up of Rectangular Walls (Isolated) (f) Close-Up of Aluminum Sheet Mirrors (Isolated)

Conclusion and Future Plans

We found that the momentum Cherenkov threshold above which each simulated accelerated particle in the pfRICH detector will begin to radiate Cherenkov photons was ≈ 0.46 GeV/c, ≈ 3.093 GeV/c, and ≈ 1.6274 GeV/c for the π^+, p^+, and K^+ particles, respectively. On the hardware side, we found that the carbon fiber-honeycomb core and plastic-honeycomb core combinations used to build the walls of the physical mock-up were strong enough to both support the weight of the main pfRICH mock-up components and to resist bending once the epoxy had cured. Future studies would propagate the predicted angular resolution of the pfRICH detector into the single-particle simulations in Geant4 to better predict the average Cherenkov angles to allow for more precise PID at higher energies.

References

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